THE IMPACT OF REFRIGERATION ON FOOD LOSSES AND ASSOCIATED GREENHOUSE GAS EMISSIONS THROUGHOUT THE SUPPLY CHAIN

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A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science (Sustainable Systems) in the University of Michigan
April 2024

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Abstract

One-third of food produced globally is wasted while approximately 800 million people suffer from hunger. Meanwhile, food losses produce approximately 8% of total anthropogenic greenhouse gas (GHG) emissions. This study develops a food loss estimation tool to assess how improved access to the cold chain could impact food loss and its associated GHG emissions for seven food types in seven regions. This study estimates that poor cold chain infrastructure could be responsible for up to 620 million metric tons (Mmt) of food loss, responsible for 1.8 $GtCO_2$-eq annually. Utilizing fully optimized cold chains could save over 100 Mmt of fruit and vegetable loss in South & Southeast Asia and over 700 Mmt CO2-eq in Sub-Saharan Africa. Developing more localized, less industrialized ("farm-to-table") food supply chains in both industrialized and non-industrialized contexts may save greater quantities of food than optimized cold chains. Utilizing localized supply chains could save over 250 Mmt of roots and tubers globally (over 100 Mmt more savings than those of an optimized cold chain) and reduce GHG emissions from meat losses in industrialized regions by over 300 Mmt CO2-eq. Due to the differences in the environmental intensity of food types, cold chain investments that prioritize reducing overall food losses will have very different outcomes than those that prioritize reducing GHG emissions.

Introduction

This study uses a food loss estimation tool to quantify changes in food loss and associated greenhouse gas (GHG) emissions that may occur with the introduction or quality improvements of cold chain technology, as well as the length of a food supply chain (FSC). The analyzed scenarios illustrate the differences between more localized, less industrialized FSCs and globalized, more technologically-advanced FSCs. By modeling food losses at each stage of the supply chain, this study highlights where the cold chain can be strategically deployed and optimized to direct food system investments to reduce food losses and emissions.

Refrigerated Supply Chain ("Cold Chain")

Ideally, the cold chain provides an unbroken, controlled atmospheric environment to ensure the quality and safety of perishable products throughout all stages of a supply chain (Aung & Chang, 2014; Ma & Guan, 2009). The "cold chain" refers to both temperature and humidity control, incorporating both physical technology and logistical management (Garnett, 2007; Heard & Miller, 2019). In the context of this paper, the term "refrigeration" is used to represent the suite of cold chain interventions, which vary according to the requirements of different food types and can include cool storage, frozen storage, and humidity control with or without temperature control. With regard to food supply, the cold chain extends from farms and processing plants to retail (grocery) and foodservice operations (Garnett, 2011; Kitinoja, 2013). The cold chain provides many safety, nutritional, and health benefits. By extending the shelf life of food, the cold chain can improve and expand access to perishable foods and reduce spoilage and foodborne illness (Heard & Miller, 2019). The cold chain is also necessary for effective vaccine and antibiotic delivery (Heard & Miller, 2019). A continuous, unbroken cold chain is necessary to maximize the benefits of safety and reduce product losses; however, in many non-industrialized economies[*], cold chain elements may have inconsistent quality, continuity or lack cold chain elements entirely (Ishangulyyev et al., 2019).

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[*] There is a range of language used across authors and disciplines to describe varying levels of development – developed vs. developing countries/economies, Low- and Middle-Income Countries (LMICs) vs. High Income Countries (HICs), non-industrialized vs. industrialized countries. We have opted to use non-industrialized vs. industrialized economies since our focus is the degree to which regional economies have industrialized their food supply chains.

This study analyzes the effects of moving from the current state of inconsistent and variable quality cold chains throughout the world to an optimized system.

Broad Impacts of Food Loss and Waste

The United Nations' Sustainable Development Goals 2 and 12 mention achieving food security and improved nutrition, and addressing food losses along supply chains, respectively (UN, 2015). Delivering on these goals is critical from humanitarian, environmental, and financial perspectives and the cold chain can have a role in achieving these objectives. While estimates vary, approximately one-third of food produced globally, 1.3 Gt, is wasted, equating to approximately 4.4 GtCO2e annually (FAO, 2015; Gustavsson et al., 2011). Concomitantly, it is estimated that 720-811 million people suffer from hunger (FAO, 2020). The financial cost of food loss and waste alone (excluding fish & seafood) is $750 billion annually; this doesn't take into account the financial costs of disposal, logistics, environmental damage, nor the human potential lost if the food were effectively distributed (FAO, 2013).

Understanding where losses occur in the food supply chain is critical to addressing systemic inefficiencies that contribute to both hunger and climate change. While food loss and waste are global issues, the patterns of food loss and waste differ. In higher income, more industrialized regions, a greater proportion of food is wasted (>40%) at the consumption phase of the FSC. In lower income regions, more than 40% of food losses occur in the early stages (post-harvest and processing) of the FSC, often due to poor logistics and lack of climate control via the cold chain (Gustavsson et al., 2011). While fully-developed and under-developed cold chains are often represented as binary, mutually distinct states, the reality is that development of a cold chain is a stepwise, context-specific process. This model examines differences in refrigeration qualities (none, poor, average, good) for each stage of a FSC, as well as a comparison of long multi-stage FSCs with very short farm-to-consumer FSCs. This model can provide critical insights into the region- and food type-specific tradeoffs of cold chain implementation, thereby informing optimal FSC development.

Prior FSC-cold chain research

Research on food systems and the cold chain has been growing over the past couple decades but remains fragmented and limited in terms of direct applicability to FSC stakeholders. Most studies fall into one of two types: historically based (meta) analysis and theoretical projection models. The former uses historical data to assess trends and rationalize those trends on regional and global scales. Gustavsson et al. (2011) presents a critical meta-analysis of global FSCs, examining the stage-specific losses regionally and providing insights into the causes behind regional food losses and potential solutions. Porter et al. (2016) built upon Gustavsson's research to publish region- and food-specific emission factors for various food products and food types. The latter approach has largely utilized storage conditions, namely temperature and time, to model food degradation and loss. James & James (2010) provide one of the earlier and more robust analyses on the relationship between food loss and climate change. Several other studies have focused on cold chain development in China, utilizing conditions-based frameworks to illustrate how various environmental factors can impact shelf life and food loss (Dong & Miller, 2021; Hu et al., 2019; J. Wu et al., 2022).

More recent academic and industry studies have used historical data and development trends to model and understand how refrigeration may manifest in non-industrialized regions. Heard & Miller (2019) model the development of a Sub-Saharan African cold chain, including food losses, dietary changes, and the emissions associated with those factors. The Global Food Cold Chain Council (2015) modeled cold chain development by comparing cold chain penetration and food loss and waste data in non-industrialized regions with that of industrialized regions.

Unlike previous research, this study focuses on potential improvements that can be realized by cold chain upgrade and optimization at specific stages within the FSC, focusing specifically on partial or suboptimally functioning refrigeration. Additionally, this study explicitly compares the losses and associated emissions of shorter, less refrigerated FSCs with extended, more refrigerated FSCs.

Methods

The model's scope and components were defined, including the FSC stages, refrigeration qualities and their associated loss rates, and relevant emissions factors tied to those losses. FAOSTAT Food Balance data were input into the model to assess its efficacy and identify opportunities for regional FSC optimization. The full model is available in the **Supporting Information** and includes the option to customize FSC length, food types, regions, and loss rates to simulate a range of scenarios in addition to the results reported in this manuscript.

Defining the model's scope and components

While there is not universal consensus on the definition of food loss, it is generally understood that food losses are the quantitative and qualitative post-harvest decreases in food fit for human consumption (Chaboud & Daviron, 2017). Solutions to food loss generally focus on management or technological changes to the FSC. In contrast, the term food waste encapsulates edible food that is supplied to the consumer but is never actually eaten, with solutions focusing more on behavioral shifts (Dong & Miller, 2021; FAO, 2019; Gustavsson et al., 2011; Heard & Miller, 2019; Parfitt et al., 2010). This study focuses on food losses in the post-harvest to retail stages of the FSC (illustrated by the area within the red dotted line in **Fig. 1**). Agricultural Production and Consumption are included for context and to show the relative contribution of these stages, but interventions to reduce food loss or waste at these stages fall outside the scope of this paper as they do not pertain to management of the cold chain. Additionally, only quantitative food loss and waste is considered in this model, as qualitative changes are not reported in the datasets utilized.

In contrast to previous studies which have included five (Gustavsson et al., 2011; Heard & Miller, 2019) or seven (FAO, 2019) FSC stages, the model developed for this study is customizable and includes a maximum of ten stages. The larger number of stages does not imply a longer supply chain but provides a higher level of resolution to be able to model individual transportation and storage stages separately. In prior studies with five stages, transportation is generally embedded into other stages. In some more recent studies, transportation is represented as a single stage or data point (FAO, 2019). By including and accounting for transportation throughout the FSC, this study allows for greater differentiation between the potential impact of refrigerated transportation from earlier versus later stages which is critical considering the trend of greater early-stage food loss in non-industrialized regions (Aschemann-Witzel et al., 2015; Parfitt et al., 2010).

Fig. 1: Visual representation of 10-stage FSC and 4-stage FSC and the mass flows for food (F) and losses (L) that can be included in the model developed through this study.

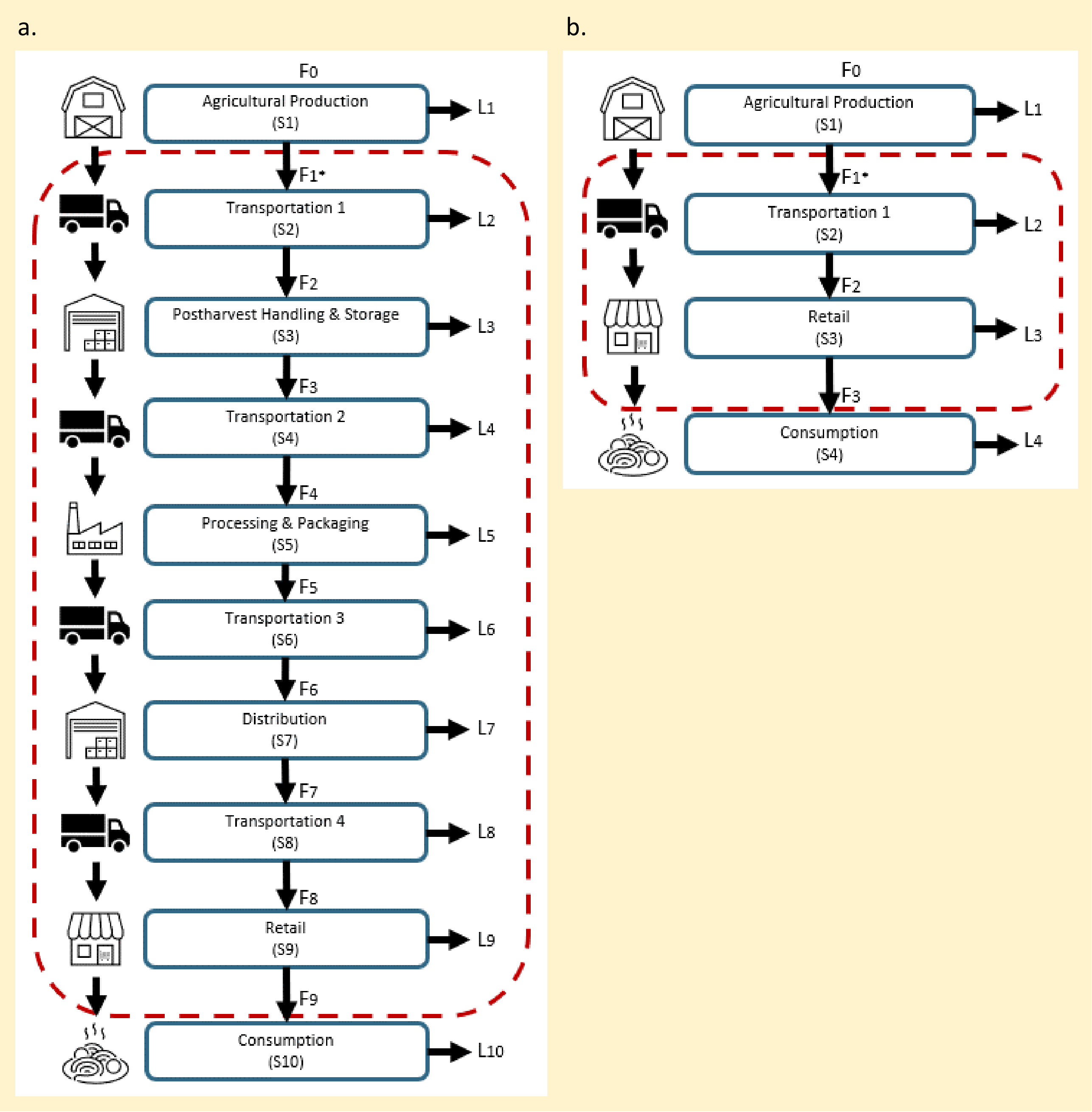


Fig. 1 illustrates both **a**, a 10-stage FSC; this was used to model all current and optimized FSC scenarios. **b,** a 4-stage FSC; this was used to model the short FSC detailed in **Fig. 5.** In both figures, Sn represents the FSC stage, Fn the food input into that stage, and Ln the food loss occurring in that stage. The red boundary indicates FSC stages that are directly impacted by refrigeration.

Model Construction

The food loss and GHG model was developed using Microsoft Office Excel. This model is based on the FSC stages and associated food loss rates defined by Gustavsson et al. (2011) and expanded upon by Dong & Miller (2021), FAO (2019), Heard & Miller (2019).

Three scenarios were modeled for every region and food type: first, a "baseline" scenario employing current loss rates across the FSC; second, an "optimized" scenario employing minimum loss rates at each FSC stage; and third, a "short FSC" scenario, employing current loss rates across a 4-stage supply chain (**Fig. 1b)**. These scenarios were used to provide nuance with the understanding that within and between regional FSCs, there is a lot of variability in terms of their robustness – the length, duration, and presence of stages. These scenarios were modeled in two ways: first, using a standard food input quantity - 100,000 kg (as shown in **Fig. 2**); second, using consumption data from FAOSTAT – due to data constraints, FSC losses were extrapolated from loss rates and applied to consumption as was done by Heard & Miller (2019) (FAOSTAT, 2023; Gustavsson et al., 2011). Ultimately, the differences in food loss and associated emissions were calculated between these scenarios, highlighting how and where refrigeration can have the greatest impact within the FSC.

Regions and Food Types

This study focuses on regions – Europe including Russia, Industrialized Asia, Latin America, North Africa & Central Asia, North America & Oceania, South & Southeast Asia, and Sub-Saharan Africa – and food types – cereals, fish & seafood, fruits & vegetables, meat, milk products, oilseeds & pulses, roots & tubers – as defined in Gustavsson et al. (2011), Heard & Miller (2019), Porter et al. (2016).

Food Loss Rates

Food loss rates at any FSC stage are influenced by a variety of factors including infrastructural, societal, logistical, behavioral, and environmental factors. Due to the complex interplay of these factors, the refrigeration quality estimates incorporate the entire range of attributes that lead to either poor or good food loss rates and do not separate out cold chain technology specifically.

Refrigeration Quality

Four refrigeration quality levels were developed for each FSC stage in the future state scenario to balance the simplicity and utility of the study. Those levels include good, average, poor, and no refrigeration, and were defined using baseline food loss rates. Good refrigeration reflects the lowest baseline loss rate, while no refrigeration reflects the highest baseline loss rate. Average and poor refrigeration are defined by the equations below:

Average Refrigeration:

$$Good\ Refrigeration\ \%\ food\ loss\ +\frac{1}{3}(max\ loss\ \%-min\ loss\ \%)$$

Poor Refrigeration:

$$Good\ Refrigeration\ \%\ food\ loss\ +\frac{2}{3}(max\ loss\ \%-min\ loss\ \%)$$

Baseline Scenario

Baseline scenarios represent current levels of refrigeration with associated loss rates derived from Gustavsson et al. (2011). To be able to model differences in refrigeration quality for transportation and storage phases, as well as distribution and retail, the 5-stage system (Gustavsson) was subdivided to a 10-stage system (**Fig. 1)**.

Optimized Scenario

Optimized scenarios represent a FSC with good-quality refrigeration across all stages by utilizing the lowest baseline loss rates for S1-S8.

Emission Factors

Food loss emission factors (which allow for calculating kg CO2e from kg food loss) were sourced from Porter et al. (2016) and Hamerschlag & Venkat (2011). These emissions factors are region- and food type-specific because different regions have different agricultural practices, inputs, energy sources, etc., producing different quantities of emissions. This model only accounts for emissions associated with food losses and does not include emissions resulting from refrigeration or other supply chain operations (e.g., transportation). For greater detail on the food types, associated foods within each food type, and their emissions, see **Section 4 of Supplementary Information**. (Heard & Miller, 2019)

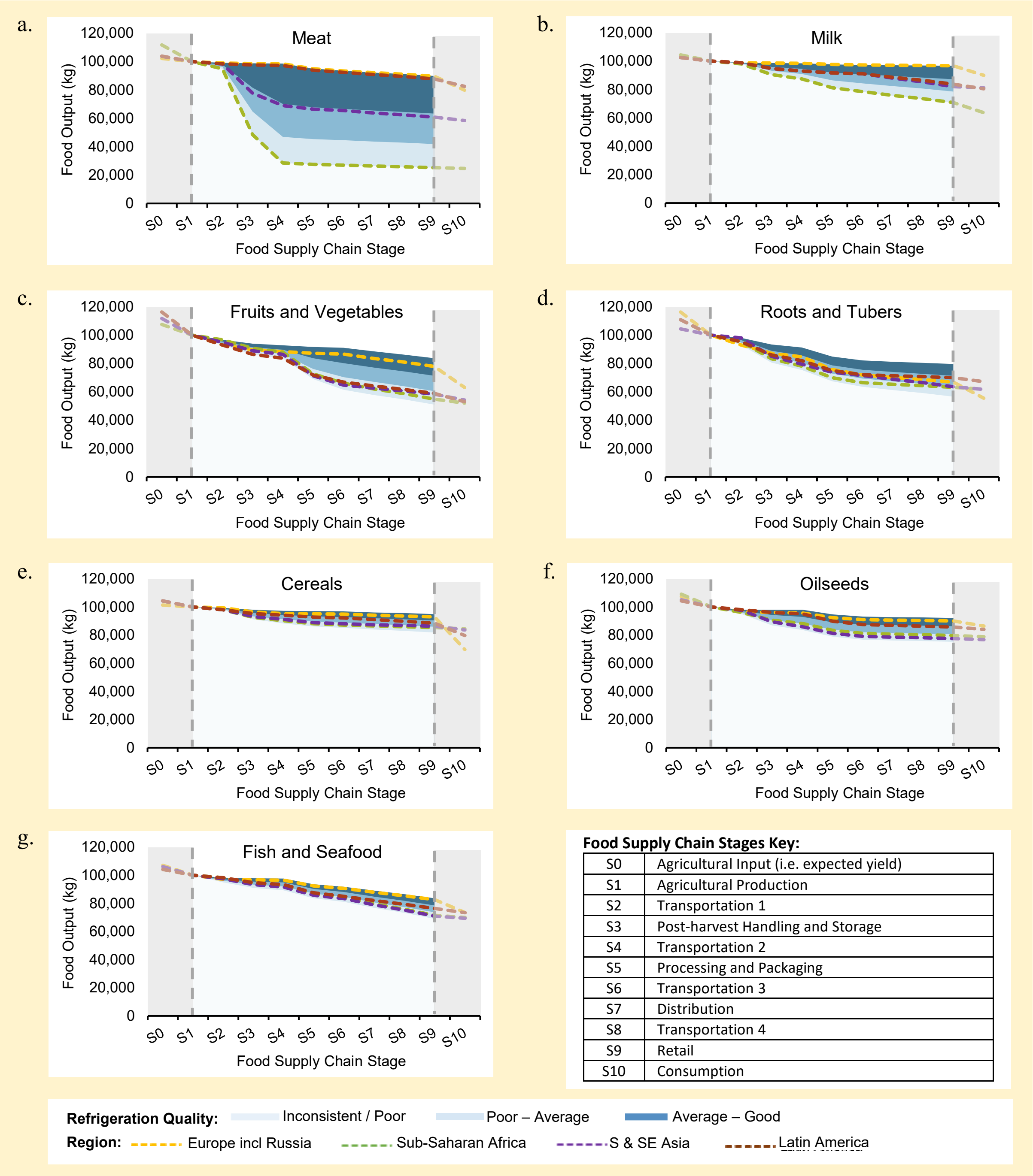
Results

The results indicate the greatest overall loss rate improvements from increased refrigeration would occur in Sub-Saharan Africa, North Africa & Central Asia, South & Southeast Asia, and Latin America, particularly with respect to meat, milk products, and fruits & vegetables.

The impact of refrigeration quality by stage and food type

The results highlight differences in how refrigeration quality affects food losses for different food types (see **Fig. 2**, which depicts food losses with respect to differences in refrigeration quality). While optimized refrigeration can reduce losses by 26-63% for milk products, fruits & vegetables, and meat, it has a lesser impact, 13-20% reduction, with respect to cereals, fish & seafood, oilseeds & pulses, and roots and tubers. This is reflected in the fact that regional differences in food losses are more pronounced for meat, milk products, and fruits & vegetables. Moreover, the results show nuances in terms of where within the FSC food losses occur, and consequently where refrigeration would be most effectively implemented. For instance, improved refrigeration implemented in post-harvest handling & storage (S2) is most effective for preventing meat loss (see **Fig. 2a**), while refrigeration implemented in processing & packaging (S4) is most effective for preventing fruit & vegetable loss (**Fig. 2c**).

Fig. 2: Food loss rates of different qualities of refrigeration for seven food types



Food Supply Chain Stages Key:

S0	Agricultural Input (i.e. expected yield)
S1	Agricultural Production
S2	Transportation 1
S3	Post-harvest Handling and Storage
S4	Transportation 2
S5	Processing and Packaging
S6	Transportation 3
S7	Distribution
S8	Transportation 4
S9	Retail
S10	Consumption

Fig. 2 shows the current mass of food loss for 100,000 kg of each food type entering the FSC at different qualities of refrigeration. The blue shading zones represent expected food losses associated with inconsistent-to-poor, poor-to-average, and average-to-good refrigeration quality, with the upper end of the top band representing consistently good refrigeration, which is considered optimal in this model. To place refrigeration quality data into context, Fig. 2 also depicts current food losses associated with four regions that represent the spectrum of existing cold chain development – Europe: fully developed, Latin America and South & Southeast Asia: partially developing, and Sub-

Saharan Africa: fully developing. While loss and waste in Agricultural Production (S1) and Consumption (S10) are displayed, they are not directly impacted by the cold chain.

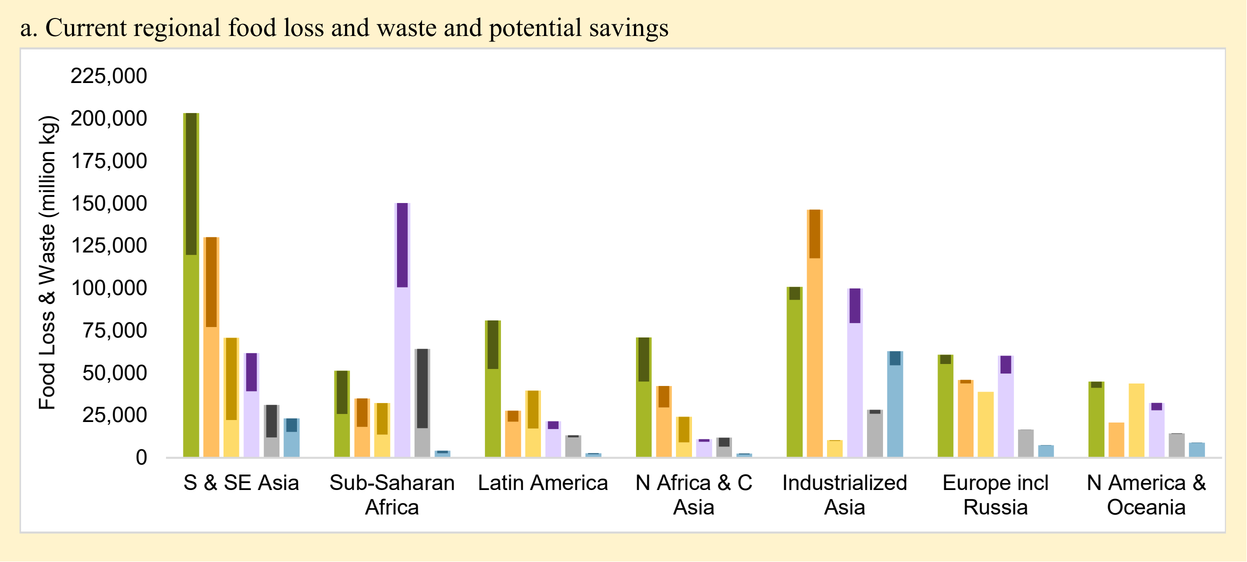
Non-industrialized regions have greater opportunity for food loss and emissions prevention through optimized refrigeration than industrialized regions

The results of modeling food loss and waste, and emissions in the FSC from Agricultural Production through Consumption (though the impact of refrigeration was only assessed post farm-gate to retail) indicate that an optimized cold chain has significant potential to improve food losses and GHG emissions, particularly in non-industrialized regions (see **Fig. 3a-b**). Meanwhile, potential improvements are relatively modest in industrialized regions that already have highly developed cold chains. Key insights can be gained regarding regional improvement opportunities, the population density of the regions, and tradeoffs between food loss versus GHG emissions savings.

On an absolute basis, South and Southeast Asia and Sub-Saharan Africa have large food losses and possess some of the greatest opportunities for improvement (**Fig. 3a**). In South and Southeast Asia, over 83 billion kg of fruits & vegetables, 53 billion kg of cereals, and 48 billion kg of milk products can be saved through optimized refrigeration (**Fig. 3a**). In Sub-Saharan Africa, over 46 billion kg of meat, and 48 billion kg of root & tubers can be saved through optimized refrigeration (**Fig. 3a**). Meat losses dominate the results for GHG emissions associated with food loss, which is to be expected given the high GHG intensity of meat production. Nevertheless, **Fig. 3b** shows a striking opportunity for improvement. Sub-Saharan Africa's potential meat savings translate to a 700 MmtCO2-eq reduction (**Fig. 3b**). Meanwhile, fruits & vegetables, cereals, and roots & tubers in both regions produce few emissions relative to their high loss quantities (**Fig. 3b**).

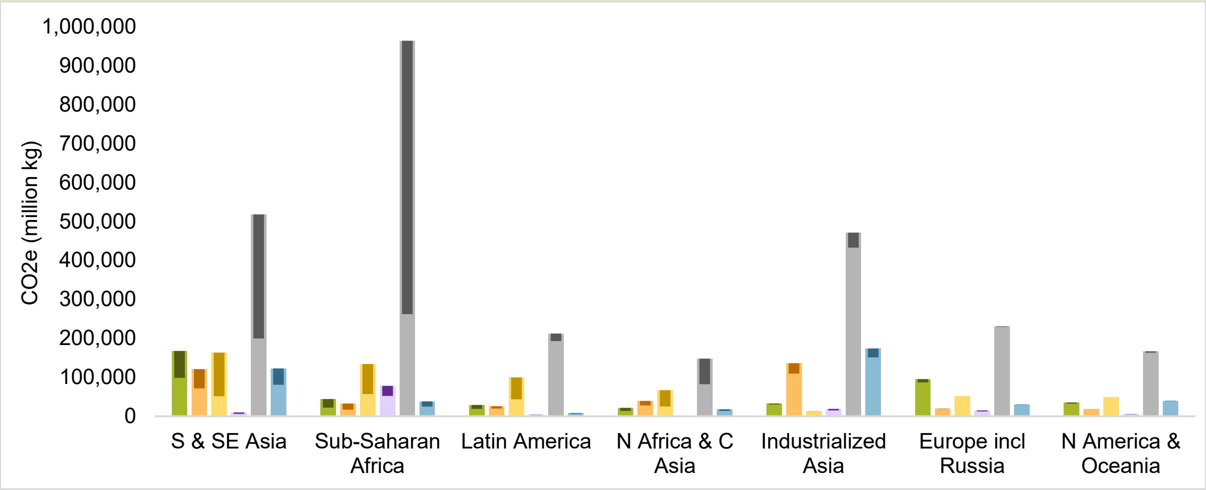
Fig. 3c-d illustrate the results when population is considered. While exhibiting some of the lowest absolute food loss and waste, and emissions, North America & Oceania has the most or second-most food loss and waste on a per capita basis across four of the six food types**.** Nevertheless, the overall improvement potential via cold chain optimization in North America & Oceania is low. Meanwhile, South & Southeast Asia has the largest absolute food losses, but lowest per capita food losses under current conditions. Despite these low per capita food losses, South & Southeast Asia has the potential to experience a 45% reduction in food losses and a 54% decrease in the associated emissions under an optimized refrigeration scenario. In contrast, Sub-Saharan Africa has the largest absolute and per capita food loss emissions, and tremendous opportunities for both food loss (47%) and emissions reduction (66%) under optimized refrigeration conditions.

Fig. 3: Regional food loss and waste, and associated emissions under current and optimally refrigerated FSC conditions

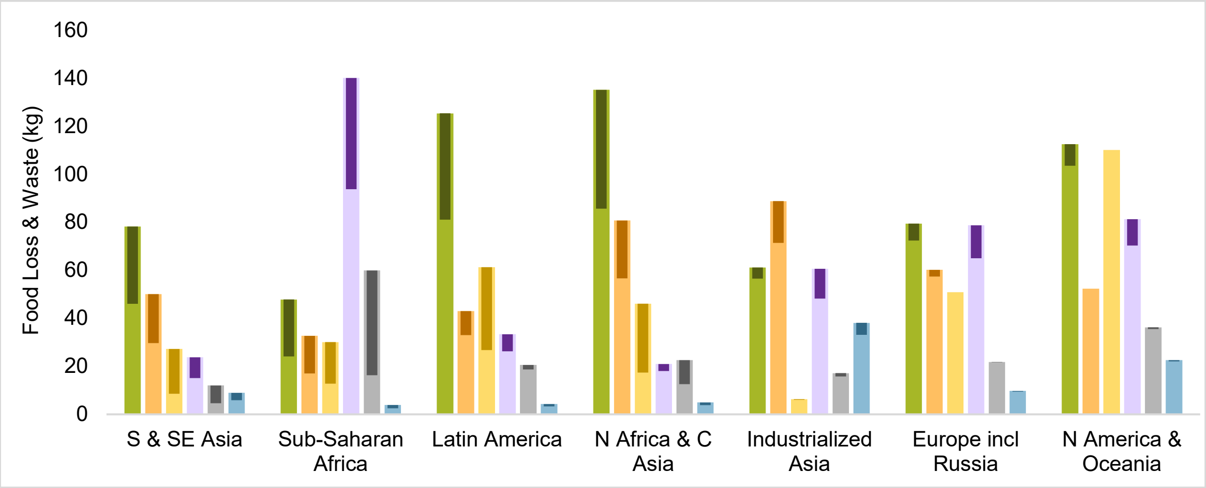


a. Current regional food loss and waste and potential savings

b. Current regional GHG emissions from food loss and waste and potential savings



c. Current per capita food loss and waste and potential savings



d. Current per capita GHG emissions from food loss and waste and potential savings

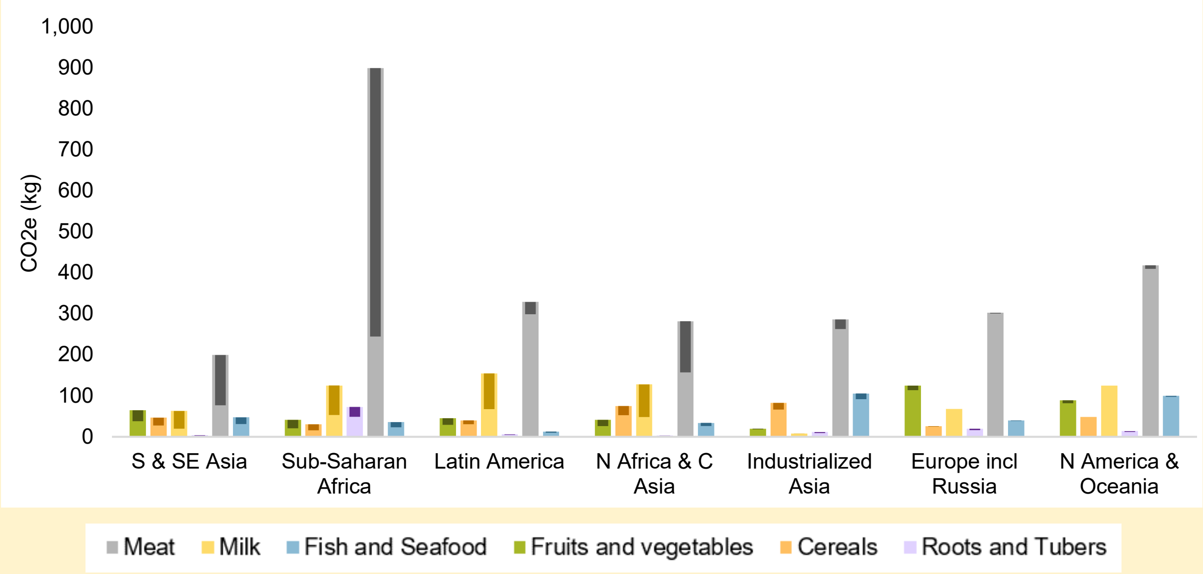
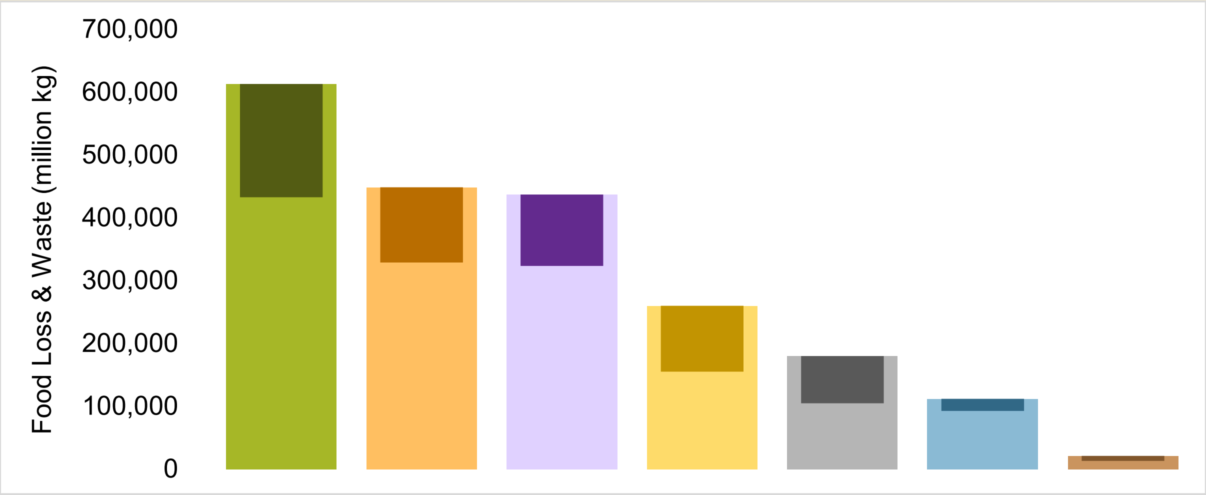


Fig. 3 shows current food loss and waste, the associated emissions, and the potential reduction opportunity of an optimized cold chain (darkened upper portions of the bars). **Fig. 3a-b** show the total quantity of regional loss and waste, and the associated GHG emissions, respectively; **c-d** show regional per capita loss and waste, and the associated GHG emissions, respectively. Oilseeds & pulses are excluded due to their small contribution.

Examining these results on a global basis, it is apparent that meat accounts for over 50% (2.7 Gt) of food loss and waste GHG emissions despite accounting for less than 10% (180 Mmt) of global food loss and waste (**Fig. 4a-b**). Optimized refrigeration of meat could result in the elimination of over 43% (1.1 Gt) of emissions associated with meat loss. Meanwhile, fruits & vegetables represent 30% of global food loss and waste but only 9% of GHG emissions. This relationship highlights a tradeoff between food loss prevention and GHG emissions mitigation and the importance of understanding this relationship when prioritizing food quantity or embodied emissions reduction.

Fig. 4: Global food losses and associated emissions under current and optimally refrigerated FSC conditions

a. Current global food losses and potential savings



b. Current global GHG emissions from food losses and potential savings

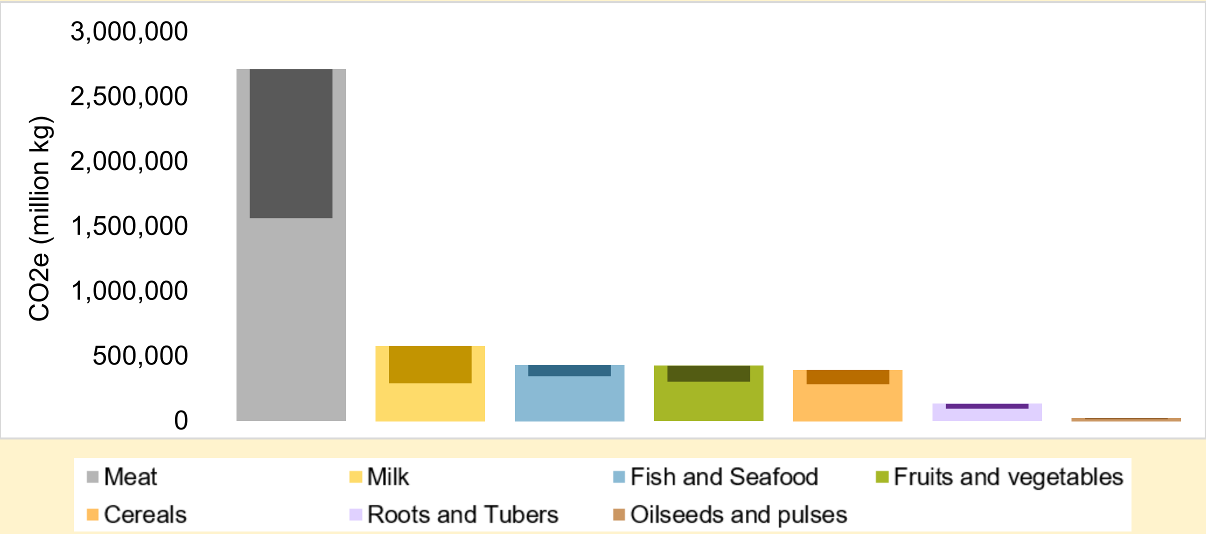


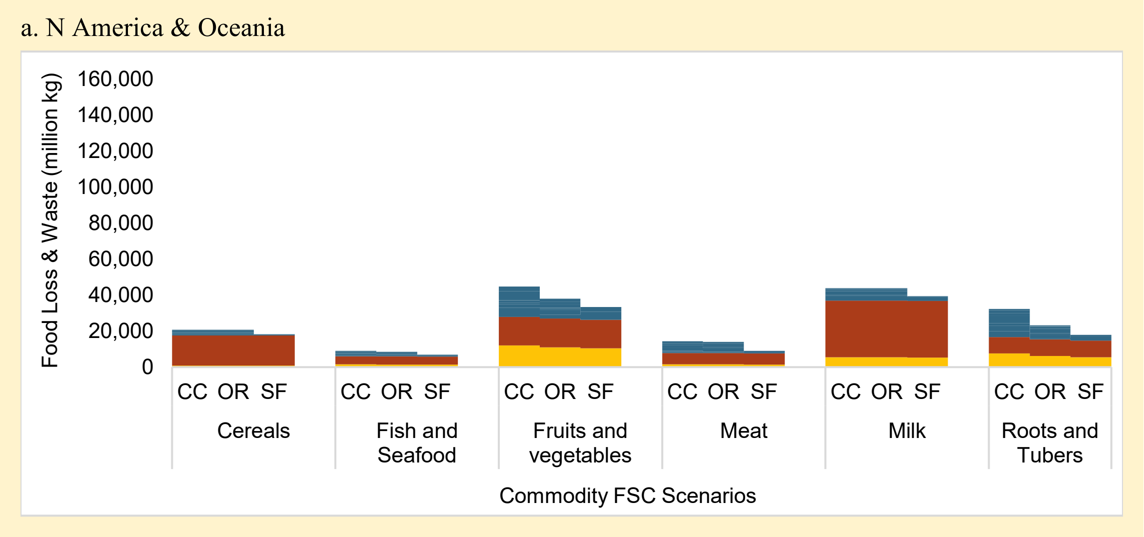
Fig. 4a-b shows current food loss and waste (**a**) and the associated emissions (**b**), and the potential reduction opportunity of an optimized cold chain (darkened upper portions) globally.

Short supply chains have a greater effect on food losses than optimizing refrigeration quality

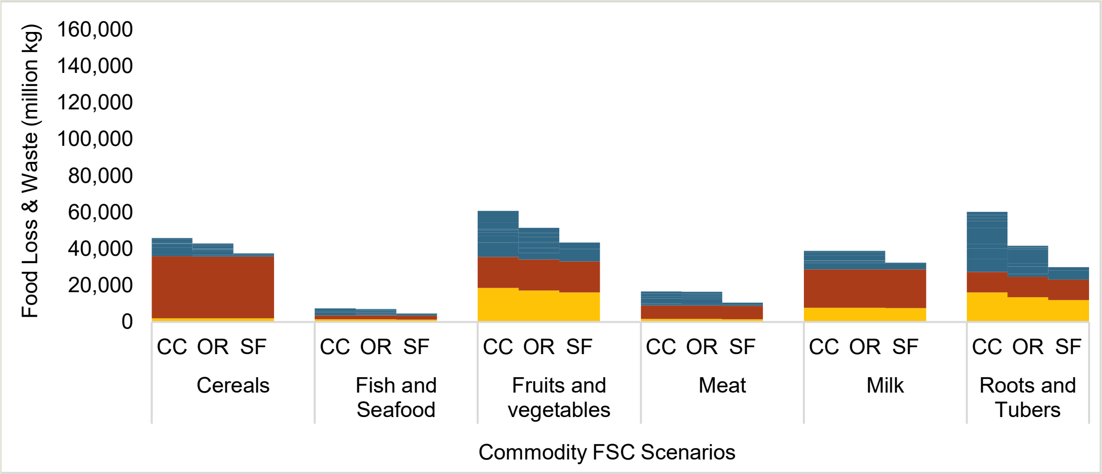
In practice, not all foods move through all stages of the supply chain shown in **Fig. 2**. Supply chains can be highly variable according to specific local conditions and specific kinds of food. To account for this variability, the extreme ends of long and short FSCs were modeled to assess potential differences between hyper-localization and optimized industrial refrigeration. **Fig. 5** highlights three different scenarios: baseline (CC), optimized (OR), and short FSC (SF), representing the current case modeled in **Figs. 2 and 3**, the optimized case modeled in **Fig. 3**, and a highly localized, "farm-to-table" food system without storage, processing, distribution, or the associated transportation stages, respectively.

Modeling these three scenarios showed that both short and longer optimized FSCs experience lower food losses compared with the baseline (**Fig. 5**). This pattern holds in non-industrialized and industrialized regions alike, though it is less pronounced in industrialized regions. This suggests that in developing contexts, improvements are possible by introducing optimized refrigeration or by making (or in many cases keeping) FSCs short. The actual feasibility of short FSCs is highly variable and dependent on geography, seasonality, and specific food type. Issues of food security and adequate nutrition, for example, are not addressed by these results. All FSCs experienced greater food loss savings from shortening the supply chain than from optimizing refrigeration. The disproportionate amount of on-farm and consumer losses in North America and Europe highlights the need for solutions addressing food loss and waste in higher income countries to focus more heavily on sources of loss outside of the actual supply chain. Despite this, it appears that shortened FSCs in industrialized regions can reduce food losses within the supply chain beyond what has already been accomplished through nearly optimal refrigeration.

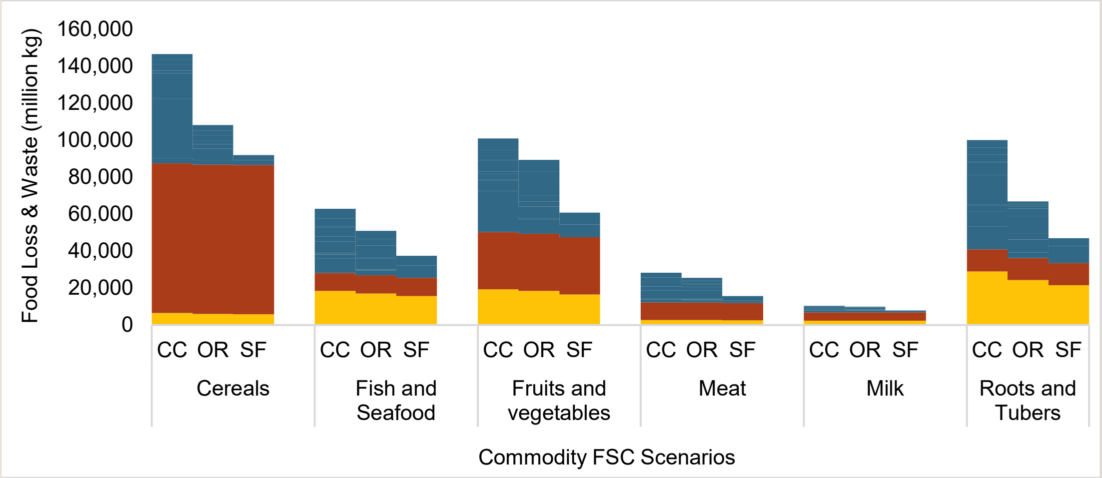
Fig. 5: The relative differences of short and long supply chains on food loss



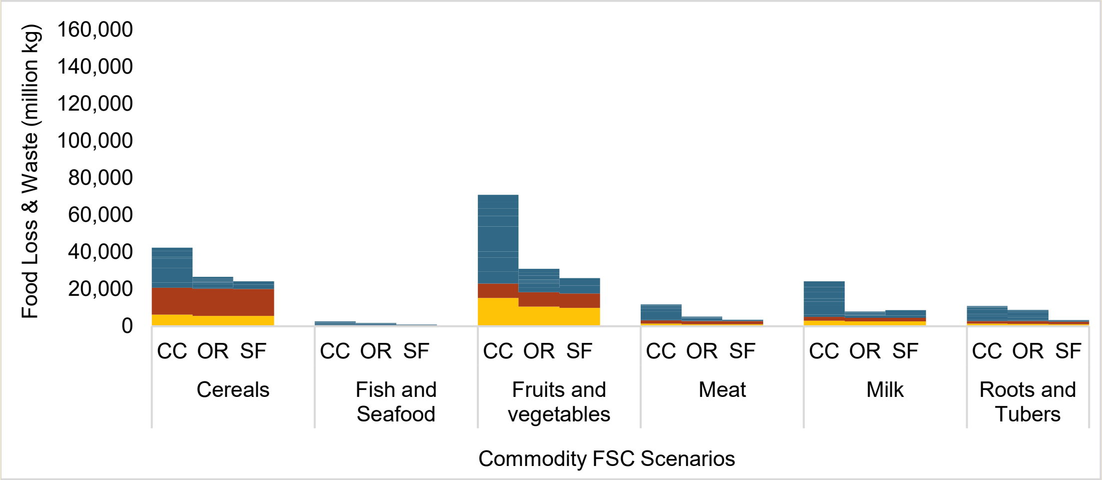
b. Europe incl Russia



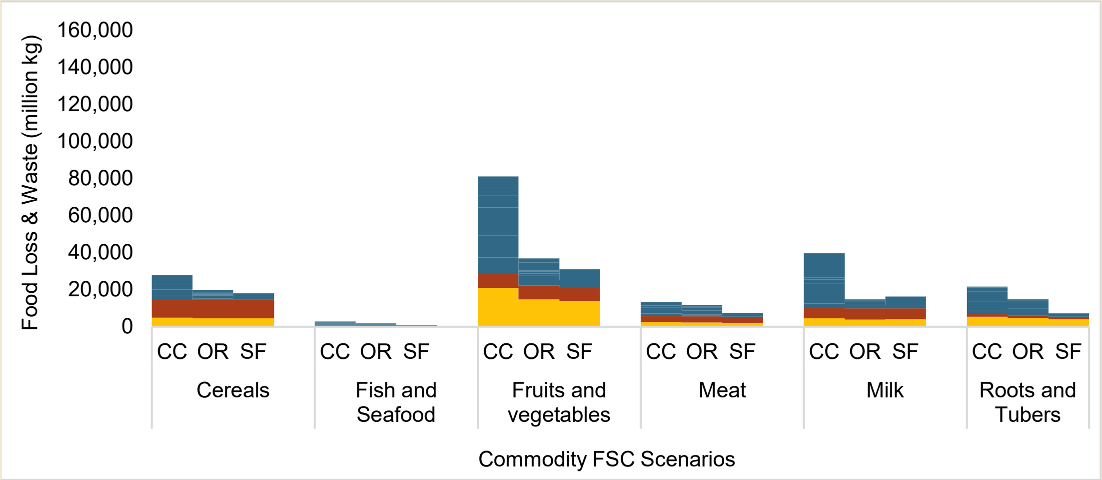
c. Industrialized Asia



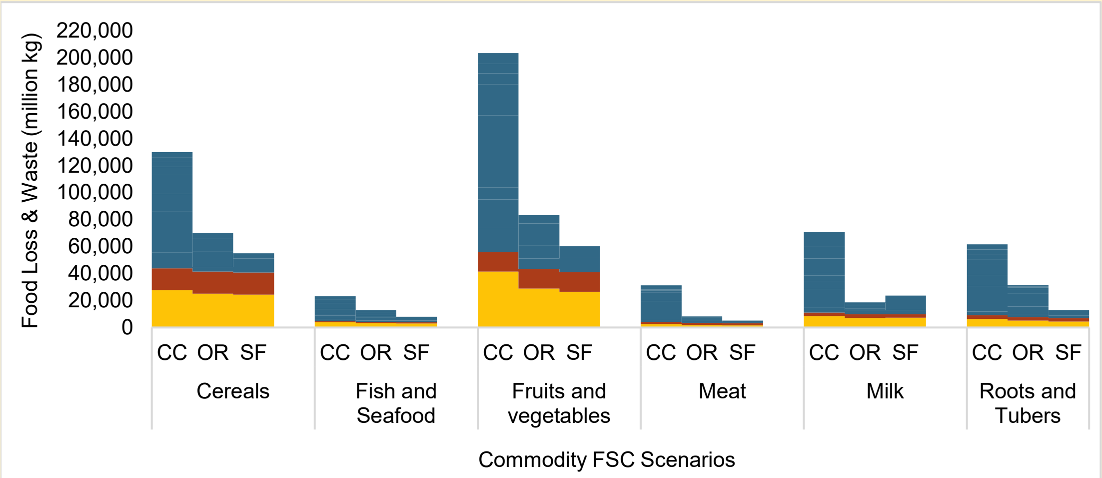
d. N Africa and C Asia



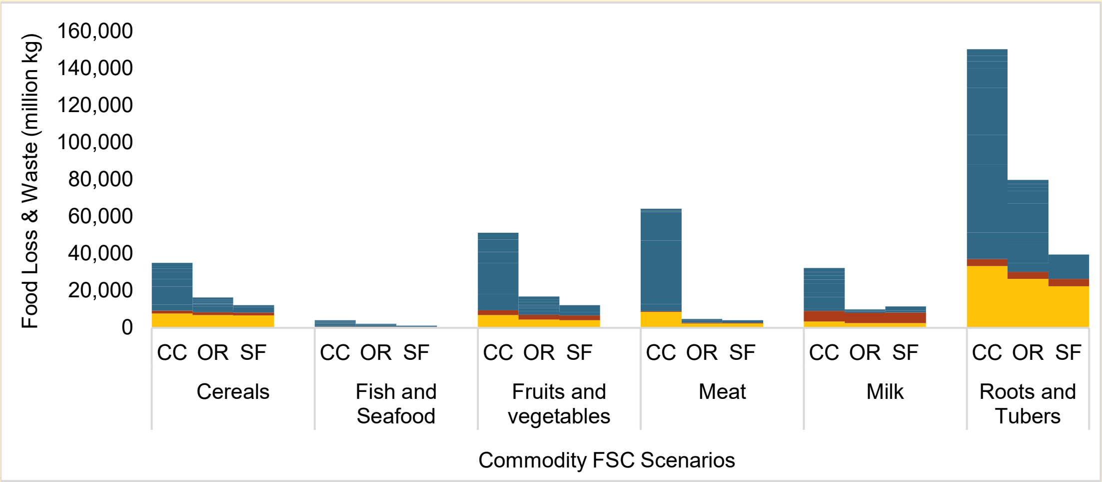
e. Latin America



f. S & SE Asia



g. Sub-Saharan Africa



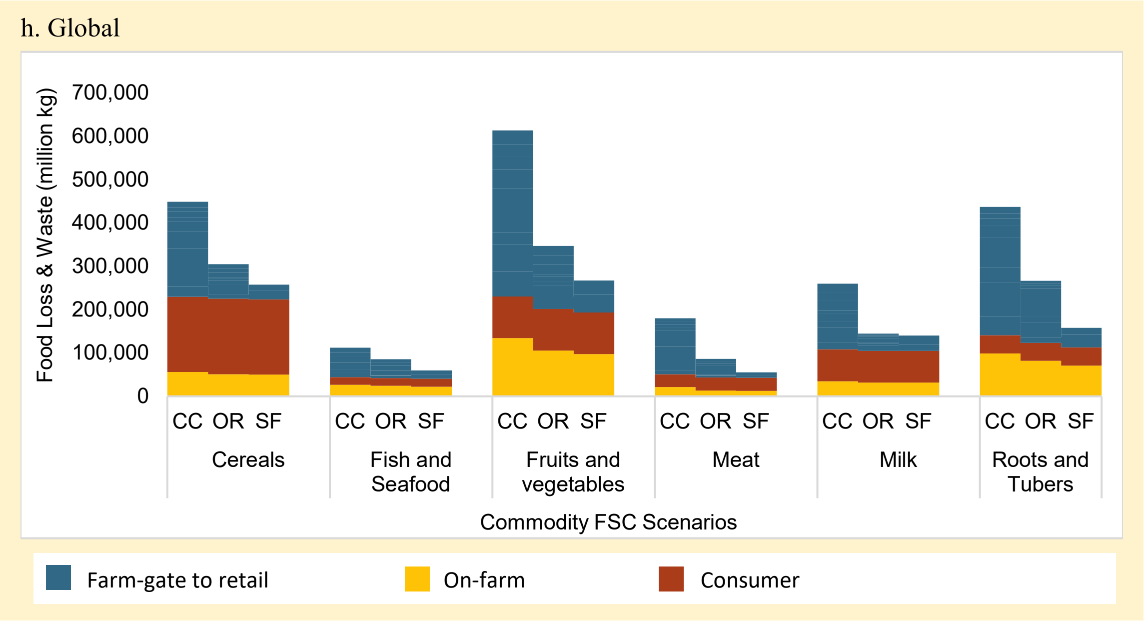


Fig. 5: Food loss and waste for six food types are modeled under three conditions: baseline (CC), optimized (OR), and short FSC (SF) (illustrated in **Fig. 1b**) regionally (**a-g)** and globally (**h**). While food loss and waste in panels **a-e** & **g** is represented on equal scales, food loss and waste in S&SE Asia (**f**) and globally (**h**) are recorded on larger scales. Unlike the previous figures, **Fig. 5** highlights both the relative contributions of food losses within the supply chain (i.e., farm-gate to retail) and those typically considered outside the supply chain. Loss and waste at all stages were calculated based on a constant state of demand (consumption), thus as food losses decrease in the farm-gate to retail stages, on-farm production loss and waste decrease. The variability in these changes is due to different regional production and consumption stage loss rates.

Discussion

Although cold chain infrastructure is rapidly increasing, an optimized cold chain will likely develop at different rates and in different ways across the globe. This analysis demonstrates that while increased refrigeration should lead to improvements in both food loss and GHG emissions associated with food loss, there are important tradeoffs associated with cold chain improvements by food type and by region. Investment decisions will need to be prioritized to maximize the desired outcomes and impacts. As previously mentioned, improved food systems are aligned with a number of the Sustainability Development Goals. If the SDG for Zero Hunger is the most important consideration, cold chain interventions that provide the greatest overall food loss reductions and best nutritional outcomes may best meet that objective. Alternatively, organizations that prioritize Climate Action may focus on reducing meat losses specifically rather than total food losses. In addition, considerations of total impact versus per capita impact have different patterns of improvement potentials.

The results indicate that Sub-Saharan Africa and South & Southeast Asia have the greatest overall potential for reductions in both food losses and emissions from increased cold chain implementation. Depending on the food type being targeted, food losses appear to experience the greatest reduction when refrigeration is implemented in the post-harvest handling & storage, transportation 2, and processing & packaging phases in non-industrialized regions. However, there are some inherent tradeoffs depending on whether improvements are targeted at reducing food loss or at reducing GHG emissions associated with food loss. As others have noted, enhanced cold chain infrastructure produces limited improvements in industrialized regions (FAO, 2015; Gustavsson et al., 2011; Heard & Miller, 2018).

Additionally, non-industrialized and industrialized regions appear to experience food loss reductions from short FSCs beyond those from optimally refrigerated FSCs. While refrigeration helps reduce food degradation rates, reduced time within the overall supply chain can have a greater effect on food loss (Abiso et al., 2015; Kitinoja, 2013; Zanoni & Zavanella, 2012). Both solutions, however, have their limitations. Short FSCs are often unable to supply adequate nutrition throughout the year due to the productivity of a region, the seasonality of agriculture, or distance from a particular food resource (i.e., fisheries). Meanwhile, optimally refrigerated FSCs necessitate that significant infrastructural preconditions (energy, roads, logistics services) be met. This speaks to the need for nuanced, regionally appropriate solutions, especially as increasing climate variability continues to shift global food production and increasingly burden global infrastructure. An “optimized” food system does not inherently mean highly globalized and industrialized for all products. While cold chain deployment can reduce food losses, it should accompany, rather than displace, robust, well-functioning localized food systems. By coupling these solutions, stakeholders can reduce food losses while simultaneously avoiding some of the energy burden and emissions impacts of refrigeration (Heard & Miller, 2019; Hu et al., 2019; International Institute of Refrigeration (IIR), 2021) and the aforementioned cultural loss and health risks.

This study provides novel insights on the potential improvements associated with cold chain introductions or upgrades; however, it has some obvious limitations. First, this study focuses solely on food losses and the associated emissions. It does not consider emissions associated with operating the cold chain nor any changes that could be induced in the system due to the presence of refrigeration, which researchers have found to produce a net increase in the overall emissions of the FSC (Heard & Miller, 2019; Hu et al., 2019; IIR, 2021). For example, studies have shown that cold chain development can change community and regional diets resulting in food systems that are increasingly energy (and emissions) intensive and dependent upon refrigeration (Garnett, 2011; Heard & Miller, 2019). Further, reductions in food loss associated GHGs only reduce the non-productive GHG emissions associated with the food system, but does not necessarily decrease total GHG emissions. Improved supply chains could lead to increased access and availability of food for human consumption, potentially redistributing food to address issues of global hunger. While this is a favorable outcome, it will not result in decreased agricultural production nor the associated GHGs.

An optimized cold chain may result in lower food loss, but does not consider a myriad of social, cultural, political, and economic factors that shape a food system. The study does not consider nutritional qualities of different food types or the social and cultural importance of food. From a technology standpoint, reliable energy infrastructure is a baseline requirement for cold chain expansion to improve access to nutrition and reduce foodborne illnesses (Aung & Chang, 2014; Mercier et al., 2018). However, in regions that lack the underlying infrastructure necessary for an effective cold chain, an ineffective cold chain coupled with a diet dependent upon cold chain infrastructure could result in greater food loss, food insecurity, and emissions while potentially weakening cultural heritage and self-sufficiency (Mercier et al., 2017; UNEP and FAO, 2022). As with air conditioning, the irony of refrigeration is that it will increasingly become a necessary tool of our FSCs as climate change worsens. Thus, as non-industrialized regions continue growing technologically and in population, it is critical to ensure that any technology deployed in these regions is implemented sustainably and in a manner that increases community resilience.

Although the analysis presented can be used to identify major trends and opportunities across regions and food types, the underlying data on actual food loss rates remain uncertain and variability can exist within regions. Projections of food losses based on historical trends do not appear to align well with theoretical food degradation models (Dong & Miller, 2021; FAOSTAT, 2023; Hu et al., 2019; W. Wu, 2019; Zanoni & Zavanella, 2012). This gap could result from many factors; for instance, others have noted that the FAO's food loss and waste data are limited and in many cases inconsistent and uncertain due to evolving definitions, varying tracking and reporting methodologies, and data access and quality limitations (Chaboud & Daviron, 2017; Lipinska et al., Parfitt et al., 2010; Xue et al., 2017). Additionally, food loss estimates could further be improved by incorporating a quality degradation factor to account for potential downstream FSC losses caused by suboptimal upstream conditions. Future work on this topic can and should account for nutritional aspects of food (i.e., calories, protein, micronutrients) instead of just total mass. While it does not directly address that gap, by adding greater flexibility to FSC models, this study provides a new way to probe the discrepancy between methodological approaches.

While the results of this study align with the results of previous studies (FAO, 2019; Gustavsson et al., 2011; IIR, 2020) relative to the percent food loss, savings opportunities, and ratios of food types within the supply chain, the quantities associated with these percentages are significantly greater in this study than in previous studies. This difference is primarily a result of methodological differences between this study and prior studies. Most previous studies utilize conversion factors to calculate the edible quantity of food produced. For example, Gustavsson et al. (2011) use a 50% conversion factor for fish and seafood, meaning that only 50% of fish and seafood produced is accounted for as food. Since a key value of this research and the model is quantifying GHG emissions associated with food loss, a conversion factor was not used. This methodology aligns with Porter et al. (2016) who cite the importance of accounting for "the entire food commodity," as any resulting loss has embedded emissions. Additionally, a small fraction of the difference in food production results in the current study reflects the increase in food produced globally over time – this research used the most recent (2020) FAO Food Balance data in contrast to that of 2009 (Gustavsson et al., 2011) and 2016 (IIR, 2020). Between 2019 and 2020 alone, the FAO reported ~500 Gt more food produced (FAOSTAT, 2023).

The findings of this study can be utilized by various FSC stakeholders. Farmers, food logistics firms, and food retailers can use this model to optimally utilize cold chain technologies to better service their customers. International NGOs and inter-governmental bodies can use it to deploy resources targeted at reducing food loss, hunger, and climate change. For example, recognizing the role of sustainable cold chain infrastructure, Germany led the UN's Green Cooling Initiative (GCI) in 2020, which "aims to reduce emissions from the cooling sectors" by prioritizing sustainable refrigerants, energy efficiency, and energy consumption" (Deutsche Gesellschaft für Internationale Zusammenarbeit; UN). This research provides a critical supplement to GCI as it answers the question of where within a given FSC, and at what intensity, refrigeration can be deployed most effectively.

Acknowledgements

This work was supported by the Carrier Corporation and the United States National Science Foundation (Grant No. CBET 1804287). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of Carrier or the National Science Foundation.

References

Abiso, E., Atheesh, N., & Addisalem, H. (2015). Effect of storage methods and ripening stages on postharvest quality of tomato (lycopersicom esculentum mill). *Annals. Food Science and Technology*, *16*(1), 127–137.

Aschemann-Witzel, J., De Hooge, I., Amani, P., Bech-Larsen, T., & Oostindjer, M. (2015). Consumer-Related Food Waste: Causes and Potential for Action. *Sustainability*, *7*, 6457–6477. https://doi.org/10.3390/su7066457

Aung, M. M., & Chang, Y. S. (2014). Temperature management for the quality assurance of a perishable food supply chain. *Food Control*, *40*(1), 198–207. https://doi.org/10.1016/j.foodcont.2013.11.016

Chaboud, G., & Daviron, B. (2017). Food losses and waste: Navigating the inconsistencies. *Global Food Security*, *12*(June 2016), 1–7. https://doi.org/10.1016/j.gfs.2016.11.004

Deutsche Gesellschaft für Internationale Zusammenarbeit. (n.d.). *Green Cooling Initiative*. https://www.green-cooling-initiative.org/

Dong, Y., & Miller, S. A. (2021). Assessing the lifecycle greenhouse gas (GHG) emissions of perishable food products delivered by the cold chain in China. *Journal of Cleaner Production*, *303*, 126982. https://doi.org/10.1016/j.jclepro.2021.126982

FAO. (2013). Food wastage footprint. In *FAO*. www.fao.org/publications

FAO. (2015). Food wastage footprint & Climate Change. *FAO*, 1–4. http://www.fao.org/3/a-bb144e.pdf

FAO. (2019). *The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction.* License: CC BY-NC-SA 3.0 IGO.

FAO. (2020). Food Security and Nutrition in the World the State of Transforming Food Systems for Affordable Healthy Diets. In *the State of the World*. https://doi.org/10.4060/ca9692en

FAOSTAT. (2023). *Food and Balance Sheets 2020*. https://www.fao.org/faostat/en/#data/FBS

Garnett, T. (2007). Food refrigeration: What is the contribution to greenhouse gas emissions and how might emissions be reduced? *Food Climate Research Network.*

Garnett, T. (2011). Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Policy*, *36*, S23–S32. https://doi.org/10.1016/j.foodpol.2010.10.010

Global Food Cold Chain Council. (2015). *Assessing the potential of the cold chain sector to* *reduce GHG emissions through food loss and waste reduction*. *October*. http://naturalleader.com/wp-content/uploads/2016/04/coldchainGHGemissionstudy.pdf

Gustavsson, J., Cederberg, C., & Sonesson, U. (2011). *Global food losses and food waste: Extent, causes and prevention*. *January*.

Hamerschlag, K., & Venkat, K. (2011). *Meat Eater's Guide to Climate Change and Health*.

Heard, B. R., & Miller, S. A. (2018). Supporting Information for "Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System." *ACS Publications*, S1–S16.

Heard, B. R., & Miller, S. A. (2019). Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System. *Environmental Science and Technology*, *53*(1), 251–260. https://doi.org/10.1021/acs.est.8b05322

Hu, G., Mu, X., Xu, M., & Miller, S. A. (2019). Potentials of GHG emission reductions from cold chain systems: Case studies of China and the United States. *Journal of Cleaner Production*, *239*, 118053. https://doi.org/10.1016/j.jclepro.2019.118053

IIR. (2020). *The role of refrigeration in worldwide nutrition: 6th Informatory Note on Refrigeration and Food*. 11. https://iifiir.org/en/fridoc/6-lt-sup-gt-th-lt-sup-gt-informatory-note-on-refrigeration-and-food-the-role-142029

IIR. (2021). The Carbon Footprint of the Cold Chain. *IIR/IIF*. https://doi.org/10.18462/iir.INfood07.04.2021 IIF

Ishangulyyev, R., Kim, S., & Lee, S. H. (2019). *Understanding Food Loss and Waste-Why Are We Losing and Wasting Food?* https://doi.org/10.3390/foods8080297

James, S. J., & James, C. (2010). The food cold-chain and climate change. *Food Research International*, *43*(7), 1944–1956. https://doi.org/10.1016/j.foodres.2010.02.001

Kitinoja, L. (2013). Use of cold chains for reducing food losses in developing countries. *PEF White Paper*, *6*(13), 1–16.

Ma, G., & Guan, H. (2009). The application research of cold-chain logistics delivery schedule based on JIT. *2009 International Conference on Industrial Mechatronics and Automation, ICIMA 2009*, 368–370. https://doi.org/10.1109/ICIMA.2009.5156639

Mercier, S., Mondor, M., Villeneuve, S., & Marcos, B. (2018). The Canadian food cold chain: A legislative, scientific, and prospective overview. *International Journal of Refrigeration*, *88*, 637–645. https://doi.org/10.1016/j.ijrefrig.2018.01.006

Mercier, S., Villeneuve, S., Mondor, M., & Uysal, I. (2017). Time–Temperature Management Along the Food Cold Chain: A Review of Recent Developments. *Comprehensive Reviews in Food Science and Food Safety*, *16*(4), 647–667. https://doi.org/10.1111/1541-4337.12269

Parfitt, J., Barthel, M., & MacNaughton, S. (2010). Food waste within food supply chains: Quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 3065–3081. https://doi.org/10.1098/rstb.2010.0126

Porter, S. D., Reay, D. S., Higgins, P., & Bomberg, E. (2016). A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. *Science of the Total Environment*, *571*, 721–729. https://doi.org/10.1016/j.scitotenv.2016.07.041

UN. (2012). *The Green Cooling Initiative*. https://sdgs.un.org/partnerships/green-cooling-initiative

UN. (2015). Resolution adopted by the General Assembly - Transforming our world: the 2030 Agenda for Sustainable Development. In *In Seventieth Session Agenda Items 15 and 116*. https://doi.org/10.1163/157180910X12665776638740

UNEP and FAO. (2022). *Sustainable Food Cold Chains: Opportunities, Challenges and the Way Forward*. https://doi.org/10.4060/cc0923en

Wu, J., Li, Q., Liu, G., Xie, R., Zou, Y., Scipioni, A., & Manzardo, A. (2022). Evaluating the impact of refrigerated transport trucks in China on climate change from the life cycle perspective. *Environmental Impact Assessment Review*, *97*(August), 106866. https://doi.org/10.1016/j.eiar.2022.106866

Wu, W. (2019). Supplemental Materials: Environmental trade-offs in fresh-fruit cold chains by combining virtual cold chains with life cycle assessment. *Comprehensive Reviews in Food Science and Food Safety*.

Xue, L., Liu, G., Parfitt, J., Liu, X., Van Herpen, E., Stenmarck, Å., O'Connor, C., Östergren, K., & Cheng, S. (2017). Missing Food, Missing Data? A Critical Review of Global Food Losses and Food Waste Data. *Environmental Science and Technology*, *51*(12), 6618–6633. https://doi.org/10.1021/acs.est.7b00401

Zanoni, S., & Zavanella, L. (2012). Chilled or frozen? Decision strategies for sustainable food supply chains. *International Journal of Production Economics*, *140*(2), 731–736.

https://doi.org/10.1016/j.ijpe.2011.04.028

Appendix: Supplementary Information

To accompany the manuscript titled

The impact of refrigeration on food losses and associated greenhouse gas emissions throughout the supply chain

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Comprising:
16 Pages
1 Supplementary Excel File

Supporting Information Contents

Supporting Information Section 1

Food Loss Model		
Tab Title	*Contents*	*Sources*
Inputs & Results	Model Interface: In the upper portion of this page the model user provides all inputs, and in the lower portion of this page all outputs are presented based upon the user's inputs	
Baseline Loss Rates	Table containing stage-by-stage loss rates for every commodity within every region	Dong & Miller (2021), Gustavsson et al. (2011), Heard & Miller (2019)
Future State Loss Rates	Table including stage-by-stage loss rates for every commodity under each of the four refrigeration qualities	Gustavsson et al. (2011)
Baseline Calculations	Backend processes for calculating Baseline outputs based on inputs	
Future State Calculations	Backend processes for calculating Future State outputs based on inputs	
Sources and Assumptions		
Tab Title	*Contents*	*Sources*
Gustavsson Loss Rates	Table containing original loss rates established in Gustavsson et al. (2011)	Gustavsson et al. (2011)
Key Assumptions	Lists all assumptions embedded in the model. Each assumption highlighted in yellow is toggle-able to account for differences in user-context	
Gustavsson w.Assumptions	Tables providing the values and processes for calculating Future State Loss Rates	Gustavsson et al. (2011)
FL Emission Factors	Table containing food loss emissions factors for all products and commodities	Hamerschlag & Venkat (2011), Porter et al. (2016))
FAOSTAT Data		
Tab Title	*Contents*	*Sources*
Updated Regions	Tables including and comparing regions originally included in Gustavsson et al. (2011) model and this model	Gustavsson et al. (2011)
Updated Food Types	Tables including and comparing commodities originally included in Gustavsson et al. (2011) model and this model	Gustavsson et al. (2011)
Appendix for Model Function		
Tab Title	*Contents*	*Sources*
FAO Regional Consumption 2020	2020 FAO Food Balance data consolidated into the seven regions and commodities utilized in the model	FAOSTAT (2023)
Simplified FL Emission Factors	Table containing solely "Other" product emissions factors for all commodities	
Data Validation	Lists used for data validation to ensure model functionality	

Supporting Information Section 2

Isolating refrigeration quality as a determinant of food loss

While many variables can affect food losses in an FSC, this study focuses solely on how refrigeration impacts food losses and therefore assumes a direct relationship between regional FSC losses and refrigeration quality. Those factors unaccounted for in this study include, but are not limited to:

Societal/Infrastructural	**Logistical**	**Behavioral**	**Environmental**
Energy infrastructure	Road quality	Driver quality	Ambient temperature
Grid reliability	Packaging type including coatings	Food handling	(Extreme) Weather
Political instability and war	Refrigerant utilized and refrigerant leaks	Change in diet due to refrigeration	Humidity
	Climate-controlling technology		Pests

Retail Food Losses

Retail exists in a definitional gray space with respect to whether discarded food should be considered waste or loss because consumer behaviors heavily influence supplier management decisions (e.g., grocery retailers choosing to over-purchase) (FAO, 2019). In this study, food discarded in the retail stage (S8) is considered food loss as it is directly impacted by supply chain management and refrigeration.

Supporting Information Section 3

Baseline Scenario: Adapting Gustavsson et al. (2011) Loss Rates

Accounting for transportation between static phases and breaking apart distribution and retail into distinct phases resulted in the creation of a 10-stage supply chain from the original 5-stage FSC used by Gustavsson et al. (2011), Heard & Miller (2019), Porter et al. (2016). The process of expanding the FSC began with adding distinct transportation phases. For this, transportation was assumed after every static phase until Retail (S8) (as that is traditionally the final non-consumer logistical phase of the FSC). This resulted in four transportation phases. Since transportation cannot be disaggregated from the FSC stages modeled by the FAO and others, expert judgment was used to determine 30% of the loss rate from Gustavsson's original static phase as an appropriate allocation for transportation losses. For example, if Postharvest Handling & Storage accounts for 10% of fruit and vegetable loss in Latin America, 7% of loss is applied to the static phase, Postharvest Handling & Storage (L2), and 3% of loss is applied to the transportation phase (L3). Since Gustavsson's loss rates were developed relative to the amount of food entering the phase in question, the equation below was used to ensure that relative loss rates were maintained throughout the FSC.

$$\text{Original Gustavsson phase loss rate: } L_n = x\%$$

$$\text{New static phase loss rate: } L_n = \frac{7}{10}x\%$$

$$\text{Subsequent transportation rate: } L_{n+1} = (\frac{3}{10}x\%)/(1 - L_n)$$

After allocating 30% of all loss rates to transportation, distribution & retail were separated into two distinct phases, evenly splitting the remaining loss rate between the two. This 50/50 split is another assumption made using expert judgement. The equations below were applied to retain consistent loss rates which function relative to the amount of food entering the node in question:

$$\text{Gustavsson Distribution phase loss rate (less transportation): } L_4 = \frac{7}{10}x\%$$

$$\text{New Distribution phase loss rate: } L_6 = \frac{1}{2}x\%$$

$$\text{New Retail phase loss rate: } L_8 = (\frac{1}{2}x\%)/(1 - (L_6 + (L_7 * (1 - L_6))))$$

Future State Scenario:

Using baseline loss rates to model future state loss rates is an effective albeit imperfect method of examining how refrigeration can manifest in developing regions. Previous studies have used a similar method for modeling future FSC scenarios, determining that refrigeration conditions and loss rates in more developed regions presently can be used to model FSC development in developing regions in the future (Global Food Cold Chain Council, 2015; Heard & Miller, 2019). For this study, the smallest observed loss rates of the regional baseline scenarios for each commodity in each stage of the FSC was assumed to represent good refrigeration conditions. Similarly, the highest observed loss rates of the regional baseline scenarios for each commodity in each stage of the FSC were applied to unrefrigerated conditions. The range of loss values was then divided into thirds. To establish the loss rate for the Average Refrigeration scenario, one-third of the range was added to the minimum loss rate for each commodity in each stage of the FSC. To establish loss rate for the Poor Refrigeration scenario, two-thirds of the range was added to the minimum loss rate for each commodity in each stage of the FSC. The definitions and food loss rates for the different refrigeration qualities are as follows:

Good Refrigeration

Good refrigeration represents the optimal condition – when high quality refrigeration is applied throughout the FSC stage in question. To that end, the good refrigeration loss rate for any stage is the minimum baseline loss rate of that stage. For example, ~0.5% (belonging to Europe including Russia) is the minimum baseline loss rate for meat in the Postharvest handling & storage stage across all the regions. This same rate is applied as the "Good Refrigeration" rate for future state scenarios.

No Refrigeration

No refrigeration represents the worst possible conditions, producing maximum food loss. Thus, the no refrigeration loss rate for any stage is the maximum baseline loss rate of that stage.

Average Refrigeration

Average refrigeration represents a sub-optimal scenario. The associated loss rate is calculated using the following equation:

Average Refrigeration Loss Rate:

$$Good\ Refrigeration\ \%\ food\ loss\ +\frac{1}{3}(max\ loss\ \%-min\ loss\ \%)$$

Poor Refrigeration

Poor refrigeration represents the worst scenario in which refrigeration is implemented. The associated loss rate is calculated using the following equation:

Poor Refrigeration Loss Rate:

$$Good\ Refrigeration\ \%\ food\ loss\ +\frac{2}{3}(max\ loss\ \%-min\ loss\ \%)$$

<u>Calculating food-associated emissions (CO2e)</u>

Once food losses are calculated for a scenario, the appropriate food- and region-specific emission factor is multiplied by the weight of food lost to produce a value for emissions produced. Emissions are quantified in kilograms (kg) of carbon dioxide equivalents (CO2e) (Hamerschlag & Venkat, 2011; Porter et al., 2016). Emissions can be calculated for a specific stage or across the entire FSC modeled using the equation below:

Food-associated emissions (CO2e):

$$Quantity\ food\ lost\ (kg)\ \times food\ \&\ region\ specific\ emissions\ factor\ (kg\ CO2e)$$

Supporting Information Section 4

When specific food product data within a commodity category is unavailable, a general emission factor for that commodity category is applied. In the model, these general emissions factors were labeled “Other” as can be seen in **Table FL Emission Factors** in the accompanying **Supplemental Information Excel** document. The “Other” emission factors were calculated commodity-by-commodity and region-by-region by averaging every product’s emission factor within a commodity. For example, the meat commodity did not have a general emission value, therefore, an average of the regional food-associated emission values of all the products within the meat commodity were used and labeled “other” for their respective regions. Similarly, an average of Porter’s “fruit” and “vegetable” emission rates was used to establish an “other” value for the Fruits & Vegetables commodity.

Supporting Information Section 5

User Guide:
Cold Chain Development
Food Loss & Emissions Model

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Contents

Overview:

This user guide accompanies the Excel **Supplementary Information** file for the research article titled, "The impact of refrigeration on food losses and associated greenhouse gas (GHG) emissions throughout the supply chain." The file is a food loss and GHG emission model is divided into four sections:

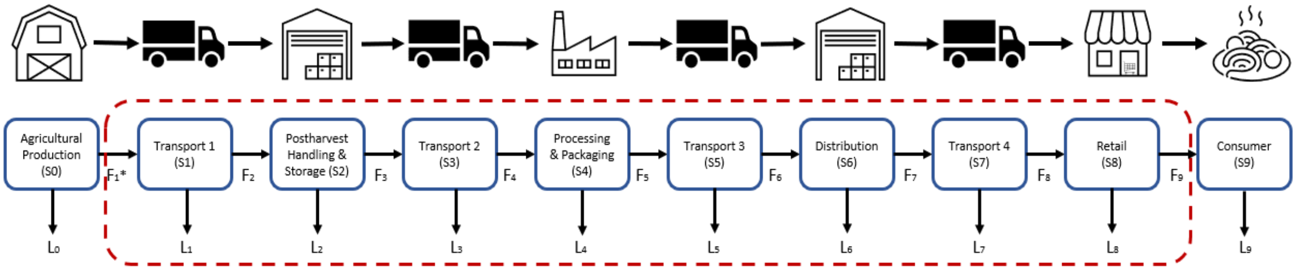
1. Food Loss and GHG Model
2. Sources and Assumptions
3. FAO Food Balance Data
4. Appendix for Model Function

The first four tabs of the Excel document comprise the core of the Food Loss and GHG Model. For more information on the model or individual tabs, see **Section 1** of the **Supplemental Information** document. The model was designed for food supply chain (FSC) stakeholders to determine how implementing or improving refrigeration for a given FSC segment can impact food losses (measured in kilograms (kg)) and the GHG emissions associated with those losses (measured in kg carbon dioxide equivalents (CO2e)). To that end, the model is customizable and includes a minimum of four FSC stages and a maximum of ten (see **Fig. 1)** to account for different FSC configurations.

The tool outputs three different "scenarios" in a three-column table (see **Fig. 5**), allowing users to compare current conditions (baseline), custom refrigeration conditions based on user inputs (future state), and maximally refrigerated conditions (optimal). The baseline scenario represents the current state of a FSC, and is calculated using prepopulated, region- and food-specific food loss rates within the model[†]. The baseline should provide users with visibility into where they are experiencing high levels of food loss within their FSC. The future state scenario allows users the opportunity to experiment with different qualities of refrigeration at the various stages within their FSC to understand how different interventions affect food losses. Based on the refrigeration qualities that the user inputs, food loss rates within the future state scenario change. The optimal scenario does not involve any user inputs; instead, the tool assumes "good" refrigeration at every stage of the designed FSC and outputs the food losses associated with good refrigeration. In other words, if the user were to choose "good" refrigeration in their future state scenario, they would notice no difference between the food losses experienced in the future state scenario and those of the optimal scenario because they have optimized refrigeration in the future state.

[†] The user can override prepopulated food loss values for both the baseline scenario and the future state scenario by inputting custom loss rates in the input section (see the right-most columns of **Figs. 3 and 4**).

Fig. 1: Maximum quantity of FSC stages, and the mass flows for food and losses that can be included in the model



Instructions for Use

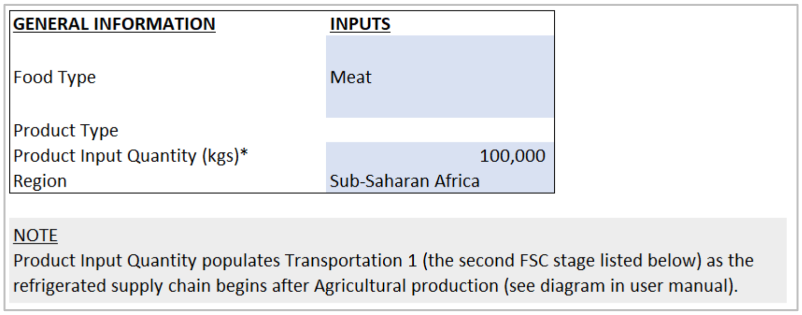
Start Here: Inputs & Results Tab

The Inputs & Results tab in the Excel model is the primary user interface of the model. This tab is the only place where user data is needed. All inputs and subsequent results are shown on this sheet. Model sources and assumptions are found on subsequent tabs for transparency.

The model may be used to either display default values estimated by the FAO or can be updated with user-defined data to model a customized supply chain.

- **General Information**
  - In the General Information section, as reflected in **Fig. 2** below, users can input food type, product type, food quantity, and region. Any details provided in General Information are applied to all three model scenarios (Baseline, Future State, Optimal). Note: users can only choose one product, type, and region at a time.
  - For the model to work, users must provide at least:
    - ***Food Type*** (dropdown)
    - ***Product input quantity (kg)***
    - ***Region*** *(dropdown)*
  - Optionally, users may input ***Product Type*** (dropdown).
    - Product Type contains some pre-populated inputs, but this list is not extensive. Users who wish to add new product types should see the **Supplemental Information** document for additional instructions.
  - Throughout the model notes are provided to further guide and inform the user.

Fig. 2: Inputs - General Information



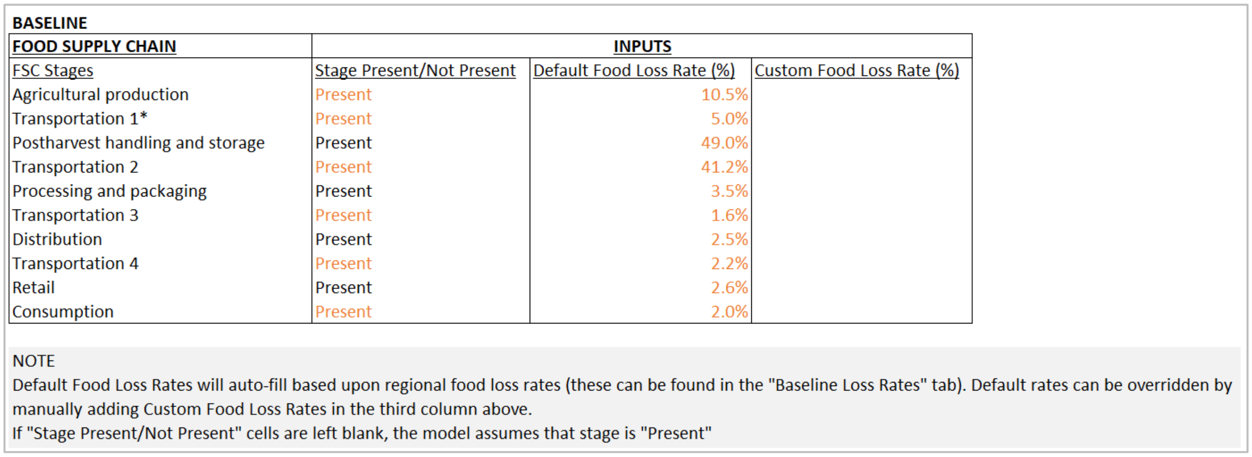
GENERAL INFORMATION	INPUTS
Food Type	Meat
Product Type	
Product Input Quantity (kgs)*	100,000
Region	Sub-Saharan Africa

NOTE

Product Input Quantity populates Transportation 1 (the second FSC stage listed below) as the refrigerated supply chain begins after Agricultural production (see diagram in user manual).

- **Baseline**
  - Once a user provides the required General Information, the Baseline Scenario will be populated with current average estimates for food losses of the food product within the defined region. While the loss rates auto-populate (See the ***Default Food Loss Rate*** column in **Fig. 3)** to regional averages, the user may override default values. If a user wishes to specify the supply chain stages present or modify the default loss rate, these can be modified in the Baseline Inputs section. Any modifications made to this section will override the default model assumptions.
  - The default loss rate values can be found in the **Baseline Loss Rates** tab.
  - Instructions for Customizing Baseline:
    - ***Stage Present*** (dropdown) – Users can determine the length of the FSC they hope to model by including and excluding certain stages. If a stage exists, users should choose "present," otherwise users should choose "not_present" to remove this step from the calculations.
      - If left unpopulated, stages are assumed present.
    - ***Custom Food Loss Rate (%)*** – For known loss rates, users can override the default value for any FSC stage by entering known loss rates in this column.
      - Note that all loss rates are relative to the amount of food entering each stage, so loss rates that sum to more than 100% (as is the case in **Fig. 3**) do not indicate a negative quantity of food.
      - Note users will receive an error message if attempting to input custom food loss rates in the ***Default Food Loss Rate*** column.

Fig. 3: Baseline Inputs



BASELINE

FOOD SUPPLY CHAIN	INPUTS		
FSC Stages	Stage Present/Not Present	Default Food Loss Rate (%)	Custom Food Loss Rate (%)
Agricultural production	Present	10.5%	
Transportation 1*	Present	5.0%	
Postharvest handling and storage	Present	49.0%	
Transportation 2	Present	41.2%	
Processing and packaging	Present	3.5%	
Transportation 3	Present	1.6%	
Distribution	Present	2.5%	
Transportation 4	Present	2.2%	
Retail	Present	2.6%	
Consumption	Present	2.0%	

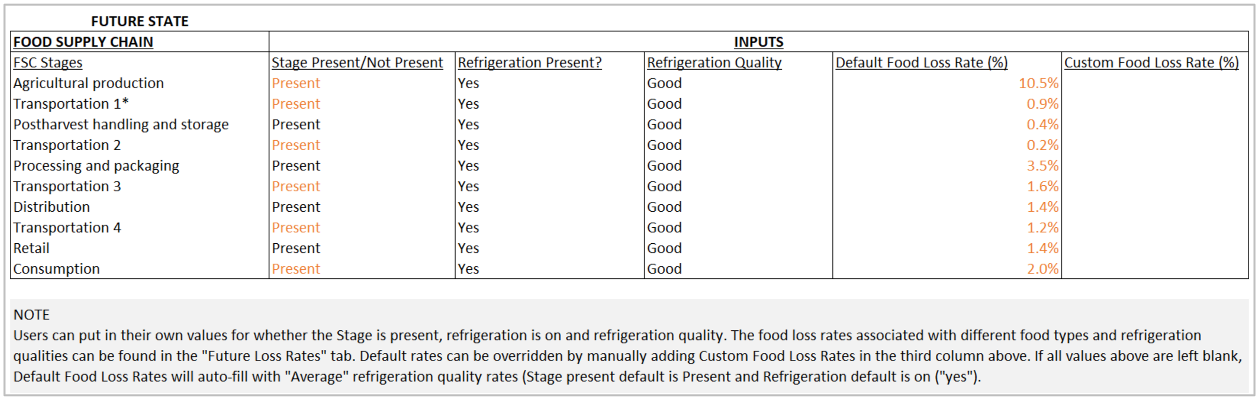
NOTE
Default Food Loss Rates will auto-fill based upon regional food loss rates (these can be found in the "Baseline Loss Rates" tab). Default rates can be overridden by manually adding Custom Food Loss Rates in the third column above.
If "Stage Present/Not Present" cells are left blank, the model assumes that stage is "Present"

- **Future State**
  - The future state scenario represents a theoretical scenario that may result from altering the existing cold chain. As the user adjusts the presence/absence and quality of refrigeration at each stage, default (auto-populating) loss rates will change accordingly. This allows users to understand the impact of refrigeration at varying qualities, in any given stage. As with the baseline, default loss rates are

overridden once a custom value is provided. The default refrigeration qualities and their associated loss rates can be found in the **Future State Loss Rates** tab. Additionally, details about how these loss rates were determined can be found in **Section 3** of **Supplementary Information**.

- ***Stage Present*** (dropdown) – Like the baseline scenario, users determine the length of the FSC modeled by including and excluding certain stages. If a stage exists, users should choose "present," otherwise users should choose "not_present" to remove this step from the calculations.
    - If left unpopulated, stages are assumed present.
- ***Refrigeration Present?*** – This is to determine whether refrigeration exists in each stage of the supply chain. Anywhere the stage exists, but lacks refrigeration, users should choose "no." For example, if an FSC has a retail stage, but that retail stage is an unrefrigerated open market, the user may choose "Present" for to ***Stage Present*** but "No" for ***Refrigeration Present?***
    - If left unpopulated, refrigeration is assumed to be present.
- ***Refrigeration Quality*** – There are three refrigeration qualities: Good (optimal), average, and poor. Users should choose the most appropriate quality of refrigeration for their future scenario. Details regarding the calculation of and values associated with the refrigeration qualities can be found in **Section 3** of **Supplemental Information**.
- If users have a custom food loss rate to provide, they should choose "Customize" in the ***Refrigeration Quality*** column and input the custom value in the ***Custom Food Loss Rate (%)*** column.
    - If left unpopulated, Refrigeration Quality is assumed to be *average.*

Fig. 4: Future State Inputs



FUTURE STATE

FOOD SUPPLY CHAIN	INPUTS				
FSC Stages	Stage Present/Not Present	Refrigeration Present?	Refrigeration Quality	Default Food Loss Rate (%)	Custom Food Loss Rate (%)
Agricultural production	Present	Yes	Good	10.5%	
Transportation 1*	Present	Yes	Good	0.9%	
Postharvest handling and storage	Present	Yes	Good	0.4%	
Transportation 2	Present	Yes	Good	0.2%	
Processing and packaging	Present	Yes	Good	3.5%	
Transportation 3	Present	Yes	Good	1.6%	
Distribution	Present	Yes	Good	1.4%	
Transportation 4	Present	Yes	Good	1.2%	
Retail	Present	Yes	Good	1.4%	
Consumption	Present	Yes	Good	2.0%	

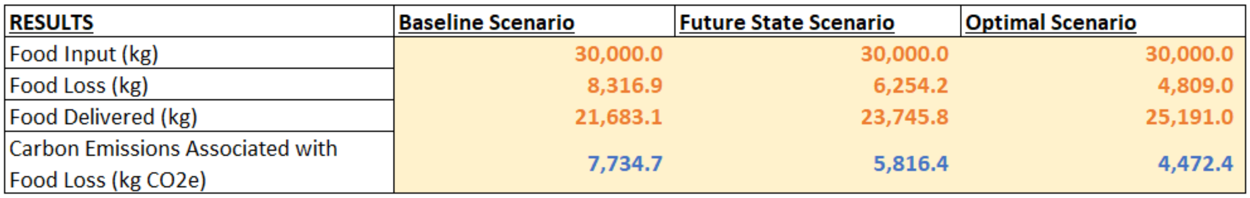
NOTE
Users can put in their own values for whether the Stage is present, refrigeration is on and refrigeration quality. The food loss rates associated with different food types and refrigeration qualities can be found in the "Future Loss Rates" tab. Default rates can be overridden by manually adding Custom Food Loss Rates in the third column above. If all values above are left blank, Default Food Loss Rates will auto-fill with "Average" refrigeration quality rates (Stage present default is Present and Refrigeration default is on ("yes").

- **Results**
    - The Results section provides the user with a comparison between the food input, food losses, food delivered, and carbon emissions for each of the three scenarios modeled - Baseline, Future State, and Optimal. The optimal scenario assumes the best (good) quality of refrigeration at every stage of the FSC and thus does not require additional user inputs to be calculated. By comparing the outputs from

each scenario, users can determine the net impact of refrigeration on food losses and the GHG emissions associated with those losses. For additional details regarding stage-by-stage outputs, losses, and emissions for any of the scenarios, review the **Baseline Calculations** and **Future State Calculations** tabs.

- **Food Input** is equal to the “Product Input Quantity” provided by the user in General Information. Thus, Food input is the same in all three scenarios.
- **Food Loss** is the sum of losses experienced in each FSC stage. These losses may vary more or less between scenarios depending on refrigeration qualities input and any custom loss values.
- **Food Delivered** is the quantity of food that reaches the consumer and equals *food input minus food losses.*
- **Carbon Emissions associated with Food Loss** is calculated by taking the product of food losses and an emissions factor. Emissions factors are region and food type dependent. For more information on the Emissions Factors, see **Section 1** of **Supplemental Information**

Fig. 5: Results



RESULTS	Baseline Scenario	Future State Scenario	Optimal Scenario
Food Input (kg)	30,000.0	30,000.0	30,000.0
Food Loss (kg)	8,316.9	6,254.2	4,809.0
Food Delivered (kg)	21,683.1	23,745.8	25,191.0
Carbon Emissions Associated with Food Loss (kg CO2e)	7,734.7	5,816.4	4,472.4

Sections 2-4

- Sections 2-4 of the excel document - Sources and Assumptions, FAO Food Balance Data, and Appendix for Model Function - provide the user details on the data and methodology that informed the model’s development and the study. For more details on any of these sections, review **Section 1** of **Supplementary Information**.

References

Dong, Y., & Miller, S. A. (2021). Assessing the lifecycle greenhouse gas (GHG) emissions of perishable food products delivered by the cold chain in China. *Journal of Cleaner Production*, *303*, 126982. https://doi.org/10.1016/j.jclepro.2021.126982

FAO. (2019). *The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction.* License: CC BY-NC-SA 3.0 IGO.

FAOSTAT. (2023). *Food and Balance Sheets 2020*. https://www.fao.org/faostat/en/#data/FBS

Global Food Cold Chain Council. (2015). *Assessing the potential of the cold chain sector to reduce GHG emissions through food loss and waste reduction*. *October*. http://naturalleader.com/wp-content/uploads/2016/04/coldchainGHGemissionstudy.pdf

Gustavsson, J., Cederberg, C., & Sonesson, U. (2011). *Global food losses and food waste: Extent, causes and prevention*. *January*.

Hamerschlag, K., & Venkat, K. (2011). *Meat Eater's Guide to Climate Change and Health*.

Heard, B. R., & Miller, S. A. (2019). Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System. *Environmental Science and Technology*, *53*(1), 251–260. https://doi.org/10.1021/acs.est.8b05322

Porter, S. D., Reay, D. S., Higgins, P., & Bomberg, E. (2016). A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. *Science of the Total Environment*, *571*, 721–729. https://doi.org/10.1016/j.scitotenv.2016.07.041